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EVIDENCE OF LARGE SCALE TECTONIC PROCESSES ON THE THARSIS RISE, MARS

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ABSTRACT

Past observations of Mars have led scientists to believe that tectonic kinematics stopped early in its planetary development. Recent exploration of Mars has led to new theories that support an active tectonic regime on the Tharsis rise. With the advancement of new satellite imagery and technologies such as Thermal Emission Imaging System, High Resolution Imaging Science Experiment satellite imagery, the Mars Orbital Laser Altimeter, and interactive software such as J-Mars and Esri GIS, we have identified additional large-scale surface features in the Tharsis Rise and surrounding areas. Large-scale Martian lineations, folds, and conjugate joints can be compared to similar structures on Earth to interpret potential plate boundaries. For example, a northeast-trending set of lineations with significant left-lateral strike-slip displacement and conjugate jointing located to the northeast of the Tharsis Rise could accommodate transform motion between two plates. Our observations allow the designation of multiple potential plate margins in the region. We propose a tectonic model showing relative motions along plate boundaries in a potentially active multiple-plate system on Mars.

Key Words: astrogeology, astro-tectonics, thermal emission imaging systems, Esri GIS software, J-Mars software, planetary geology, planetary tectonics

INTRODUCTION

During the past twenty years, exploration of the Martian surface has grown by leaps and bounds. Mars does not disappoint in its promise for breathtaking scientific breakthroughs. Two primary research topics on Mars, life and water, have been frontrunners in the Martian scientific community. Sedimentary markers of lakes, rivers, and streambeds show that the Martian paleoenvironment was quite different than today. Although conclusive evidence has not been found yet, the search for life is ongoing through surface missions with unmanned rovers trekking across the surface. The close similarity between geological structures on Earth and Mars has enabled scientists to apply known geological scientific theory to uncover the past history of Mars. With all the recent technological advances at our fingertips, another basic geological question about Mars can be asked; is there currently a form of plate tectonics on Mars?

The Tharsis rise, an area on the western hemisphere of Mars that is smaller than about one third of the planet, was the focus of this research (fig. 1). The rise boasts some of the largest volcanoes in the solar system including Olympus Mons, as well as features such as Valles Marineris (fig. 2). The technology used to analyze the surface of the Tharsis rise in this study includes the following satellite missions. In 1996 The Jet Propulsion Laboratory launched the Mars Global Surveyor with scientific instruments that included the Mars Orbital Laser Altimeter, as well as a magnetometer and electron reflectometer. Mars Global Surveyor allowed digital elevation maps to be taken of the surface as well as a measurement of the magnetic field characteristics on Mars. In 2001 Thermal Emission Imaging System (THEMIS) was carried by the 2001 Mars Odyssey satellite with one of its missions to investigate detailed geological formations on the surface. The THEMIS camera is capable of taking visual images at 59 feet or 18 meters per pixel. Mars Odyssey was later followed by the Mars Reconnaissance Orbiter, launched in 2005 with the High Resolution Imaging Science Experiment (HiRISE) satellite imagery, which is capable of taking images down to a 1 meter scale (NASA). Using J-Mars version 3.0, a Java Mission-planning and Analysis for Remote Sensing GIS program specifically developed for the study of Mars through Arizona State University's Mars Space Flight Facility, images of Mars from THEMIS, and HiRISE, has made it possible to view detailed satellite imagery. MOLA images were also used as background base maps for mapping on Esri ArcMap Version 10.2.

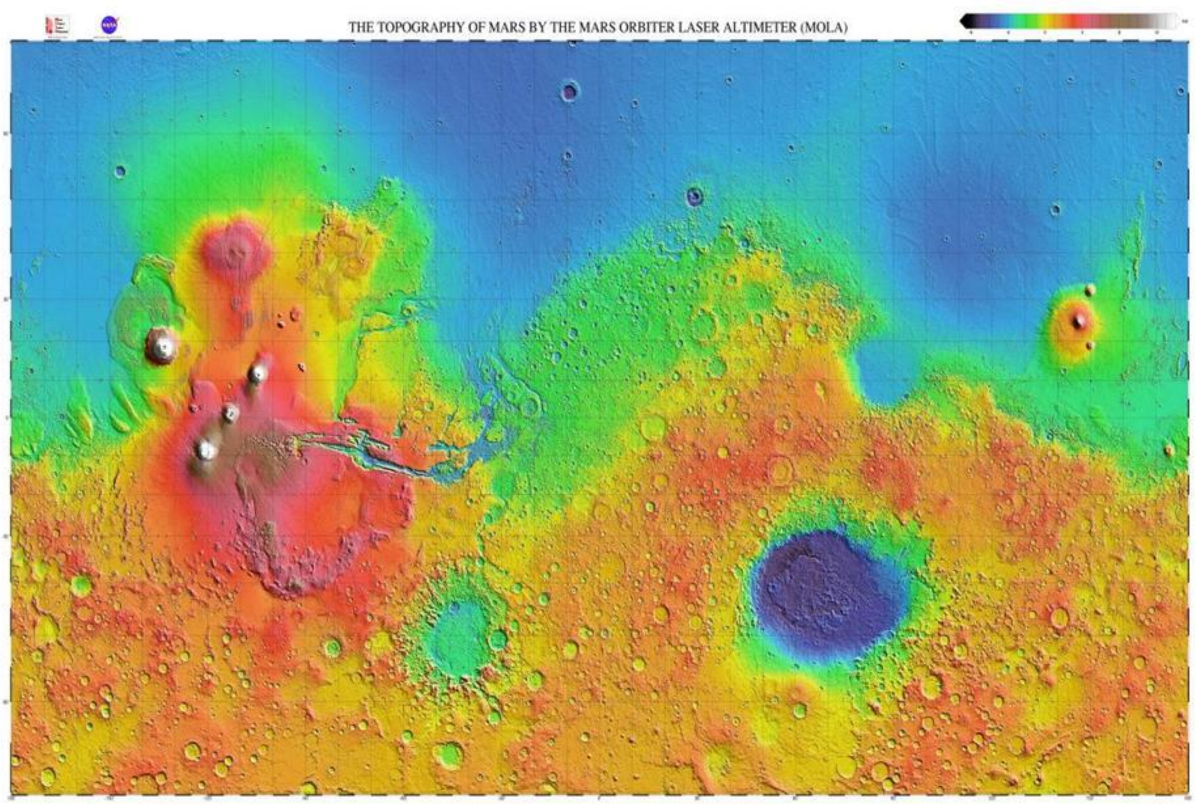

Figure 1. MOLA map of the surface of Mars (NASA, Mars global data set). The Tharsis rise is located in the western half and has prominent features such as volcanoes, mountain ranges, and deep canyons. Tharsis rise is the predominantly red areas in the western hemisphere.

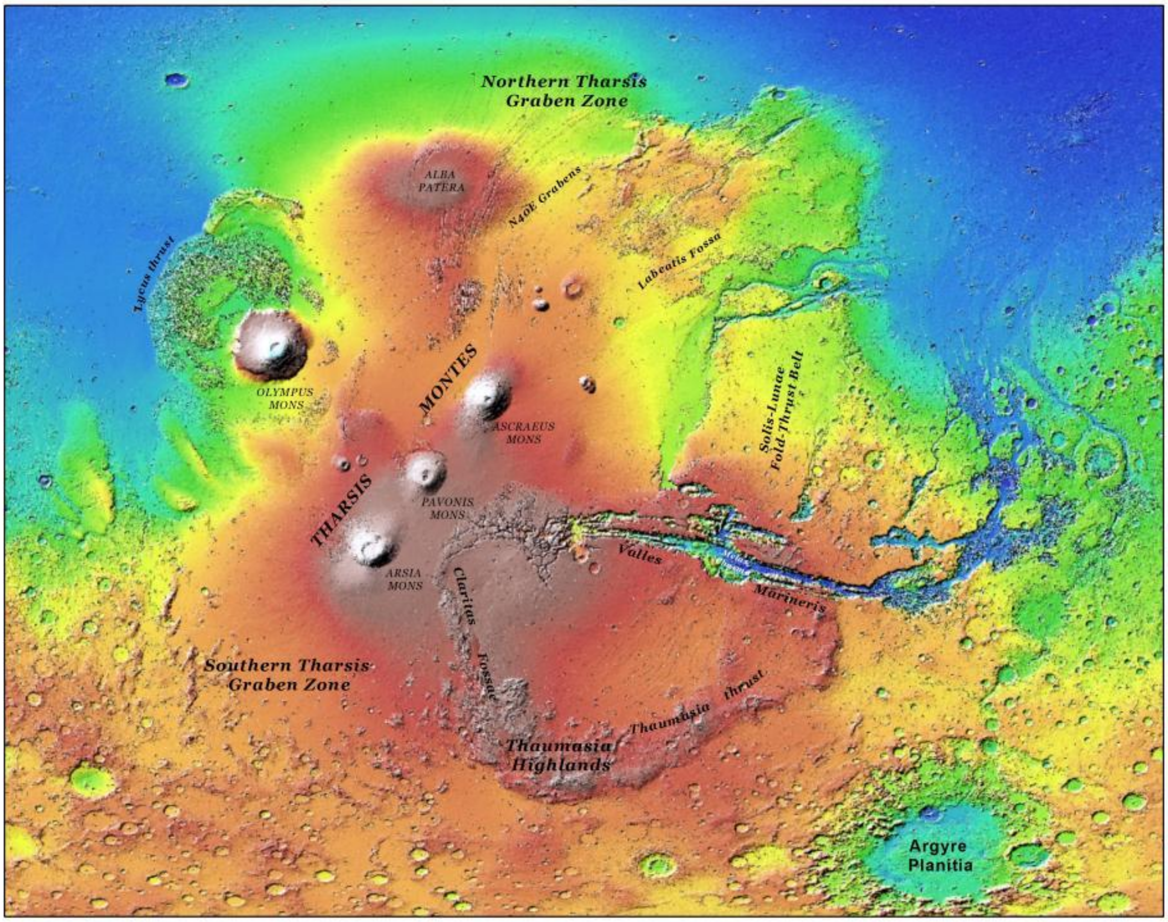

Figure 2. Tharsis Rise regional map. Background imagery from NASA.

Through these technologies and the work of other scientists, there have been recent discoveries on Mars that have shed light on the possibility of ancient and active Martian tectonics. These discoveries include the following:

- The Mars Global Surveyor found a remnant crustal magnetic field on Mars (Stanley, *et al.*, 2008) that may indicate a driving mechanism for ancient plate tectonics.
- One or more large hotspots involving volcanic construction on the lithosphere (Neukum, *et al.*, 2004) (Kiefer and Li 2007 and 2009), possibly paired with the creation of the Hellas Basin (Johnson and Phillips, 2005), likely contributed to the creation of the Tharsis Rise.
- Tectonic episodic slab rollback (Yin, 2012a), including the necessary components of a core, mantel, and crust, would facilitate the heat needed for hotspot mechanics and tectonism.
- The linear northeast trend of the Tharsis Montes, Arasia Mons, Pavonis Mons, and Ascraeus Mons, as well as numerous grabens, suggest the likelihood of a spreading center on the Tharsis Rise (Zimbelman and Edgett, 1992) (Comer, *et al.*, 1985) (Borgia and Murray, 2010).
- Transtensional, left lateral strike-slip movement with 150 kilometers of

displacement shows modern tectonism in Valles Marineris (Yin, 2012a).

- Evidence of apparently recent faulting is exposed, implying recent and possibly ongoing tectonic processes (Andrews-Hanna, *et al*., 2008) (Petrowsky, *et al.*, 2009) (Allemand, *et al.*, 2006) (Kronberg and Hauber, 2009) (Ferrill, *et al.*, 2011).
- Linear features called "wrinkle ridges" interpreted as thrust faults are aligned perpendicular to Tharsis Rise (Golombek ,1990).
- The Tharsis Rise volcanoes show evidence of activity in the past million years. In geologic time, it is possible for these dormant volcanoes to still be active (Neukum, *et al.*, 2004).
- Relative age dating and remote sensing techniques of different units on the Tharsis Rise allow comparison of relative movements (Tanaka and Scott, 1987).

This study focused on three questions stemming from the discoveries listed above to explore the possibility of current plate tectonics on Mars. First, are there Earth analogs to Martian surface features that could be used to identify tectonic processes? Second, is it possible to use Martian surface features to identify types of plate boundaries on Mars? Third, it is possible to discern relative plate motions?

GEOLOGIC SETTING AND PREVIOUS RESEARCH

Magnetic field

During its lifespan, Mars Global Surveyor was able to take measurements of the strength of the magnetic field around Mars. It indicated there is no global magnetic field presently on Mars, but a "remnant crustal magnetic field" created by highly magnetized rocks in the southern hemisphere exists. These magnetized rocks showed evidence that at one time there was a strong global magnetic field created by an ancient Martian core (Stanley, *et al.*, 2008). While this does not explain a mechanism for modern plate tectonics on Mars today, it does give a mechanism for a previously hot interior that could continue to affect boundaries seen today.

Creation of the Tharsis Rise

The Tharsis Rise may have begun to form by the Nochian, the earliest epoch on Mars, at least by 3500 Ma (Johnson and Phillips, 2005) (Yin, 2012b). Recently a new model for the creation of the Tharsis Rise has been proposed involving the start of early planetary tectonic kinematics (Yin, 2012b). Subduction of a plate to the northwest of the Tharsis rise could have been triggered by a large asteroid impact, such as the Argyre impactor, during the heavy bombardment period. This impact would have pushed the Tharsis rise region up and over its neighboring plate to the northwest. With subduction started, a slab rollback model would be able to create the Tharsis rise that is seen today. Moving from southeast to northwest, this rollback model includes evidence such as differences in structural trends, morphologies, spacing of volcanoes, as well as a lack of crustal magnetization and different faulting and crustal styles bounding Olympus Mons (Yin, 2012b). Both theories involve active tectonic processes taking place from the Nochian through early Amazonian epochs. These tectonic processes imply zones of weaknesses that would give current tectonic processes preexisting weaknesses to utilize.

The Tharsis Rise region may be influenced by mantle plumes. The plume influence hypothesis is supported by mantle convection models and observations of lithospheric thicknesses from gravity anomalies, topography, and tectonic structures (Kiefer and Li, 2007 and 2009). Additionally, magnetization data from Mars Global Surveyor indicates that thermal uplift and the creation of the Hellas Basin, antipodal to the Tharsis Rise, could have contributed greatly to the creation of the rise (Johnson and Phillips, 2005).

Linear Trends and Spreading Centers

Large scale linear features have been identified on the Tharsis rise, including the alignment of the Tharsis Montes (fig. 3). The three volcanoes that make up the Tharsis Montes, Arsia Mons, Pavonis Mons, and Ascraeus Mons, and their associated fissures or flank vents indicate a rift axis oriented N40E (Zimbelman and Edgett, 1992) (Comer, *et al.*, 1985). The Tharsis rise has also been compared with the terrestrial Mount Etna, a gravitational spreading volcano that shows strong similarities, albeit on a smaller scale, to the Tharsis Rise (Borgia and Murray, 2010).

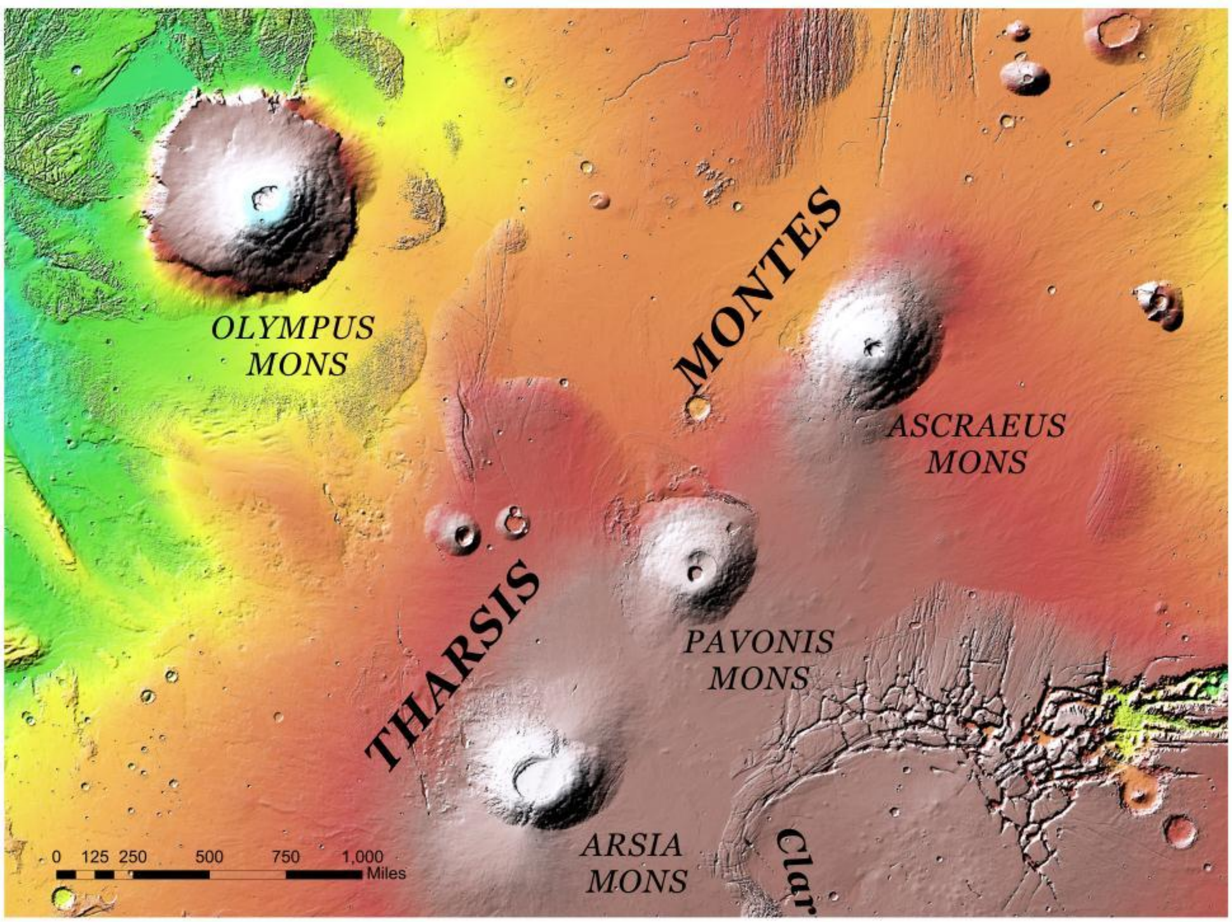

Figure 3. The Tharsis Montes, a range of aligned volcanoes on the Tharsis Rise trending N40W. Background imagery from NASA.

Large escape structures created by dilatational faults and fractures have created pit craters that are not unlike those found on Earth and other planetary bodies (fig. 4). These pit craters are created when a fracture of fault experiences extensional forces resulting in the overlying sediments flowing down into the newly open spaces below. One of the known methods to create pit craters on an escape structure would be in a tectonic environment (Ferrill, *et al.*, 2011). Numerous grabens are common on the Tharsis rise, (fig. 5) and are found trending in a general direction of northeast 45-60 degrees (Kronberg and Hauber, 2009).

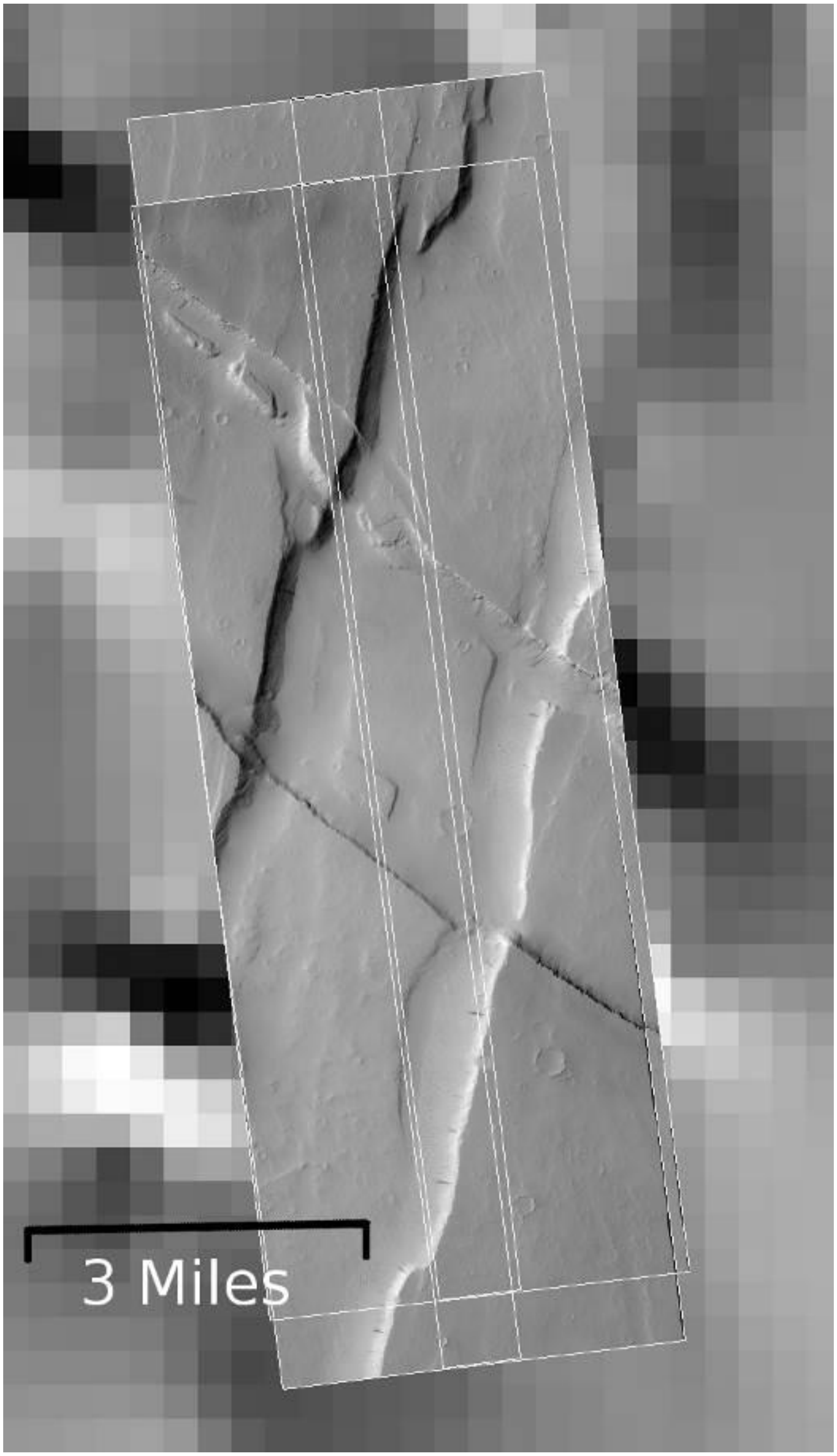

Figure 4.

Escape structures forming pit craters on the northern edge of the Tharsis Rise (J-Mars, 2013).

HiRISE Images:

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ESP_027460_2105_Red,
PSP_004912_2110-Red.
Located at 260.62E 31.11.

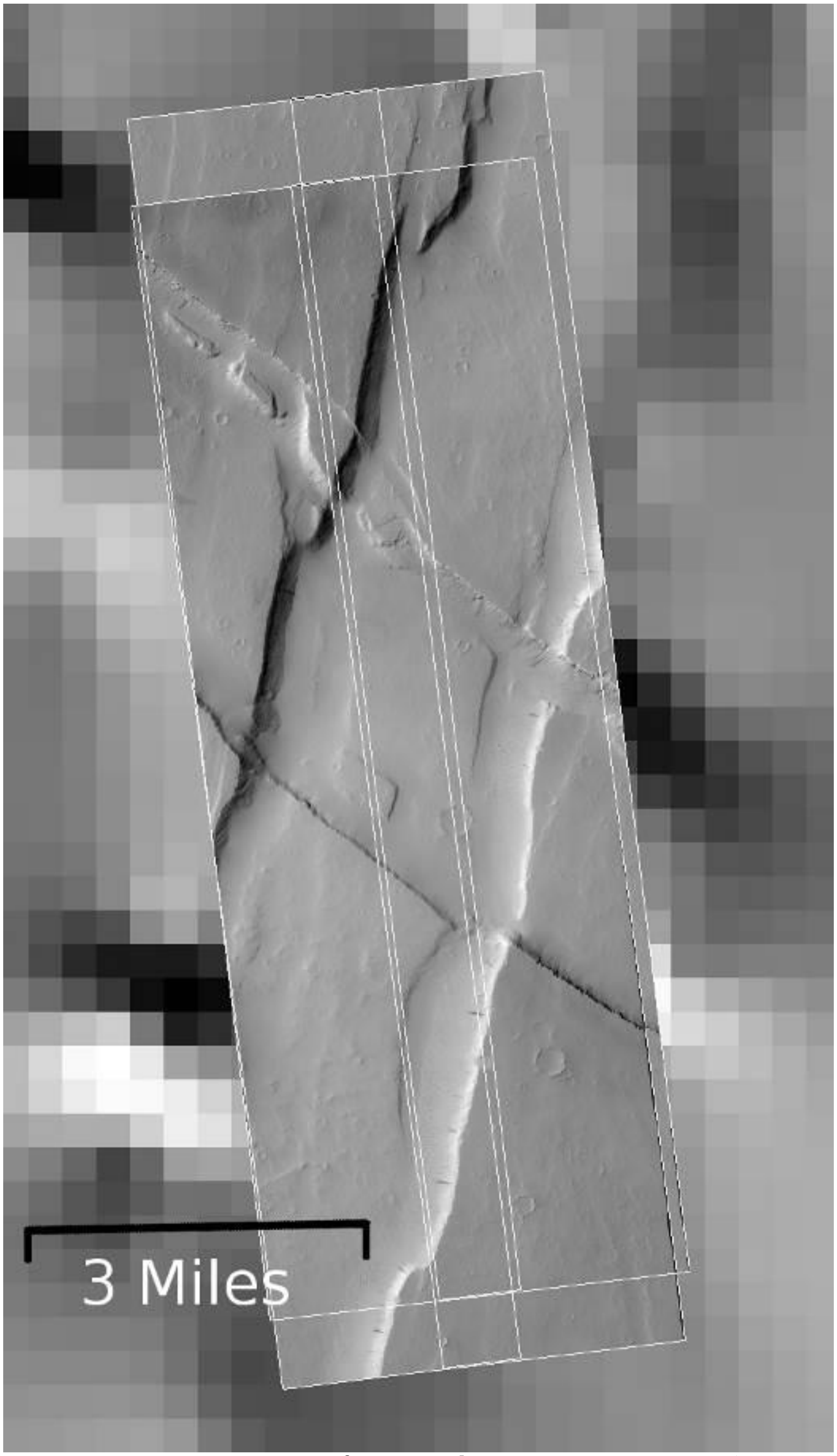

Figure 5. Conjugate jointing of two graben escape structures (J-Mars 2013). HiRISE Images: ESP_017268_1915_Red, ESP_017413_1915_Red. Located at 237.34E 11.54

Valles Marineris

The creation of the 4000 km long Valles Marineris canyon in the southeast Tharsis Rise region has been a point of varying hypotheses. Recent evidence suggests the canyon is currently a large transtensional left lateral strike slip boundary that forms half of an east-facing V-shaped conjugate strike-slip system with the Claritas Fossae fault (fig. 6) (Yin, 2012a and 2012b). The episodic slab rollback theory explains the canyon's left lateral movement and displacement along the canyon as back-arc extension (Yin, 2012b). There is recent tectonic activity in the area, accommodated by 150 km of displacement in the Melas Chasma. Fault scarps cross-cutting young talus slopes indicate very recent tectonic movement in the area (Yin, 2012a).

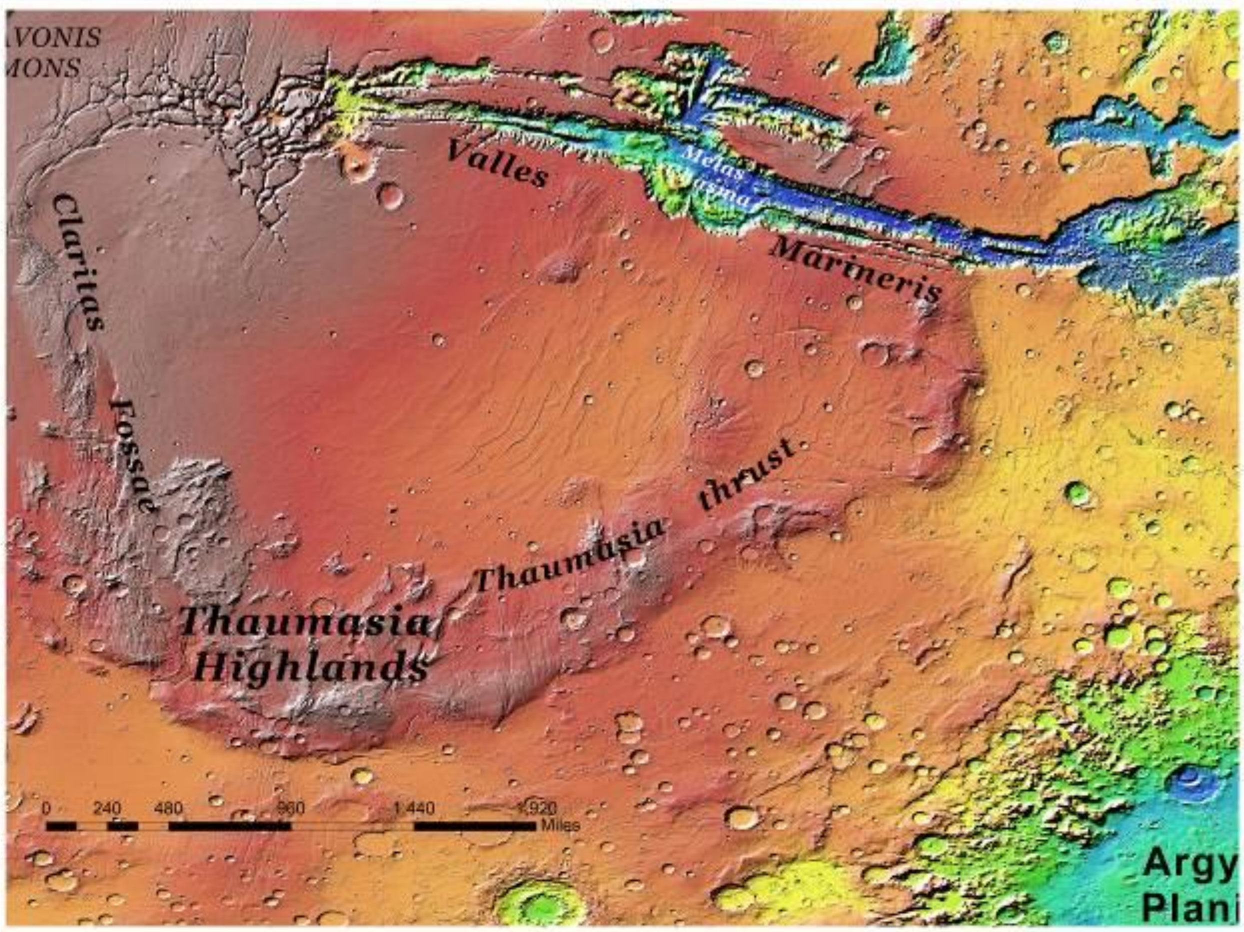

Figure 6. The Valles Marineris and Claritas Fossae strike slip system. Background imagery from NASA.

Other Prominent Faults

Well known faults include the Thaumasia thrust on the southeast side of the conjugate strike slip system, the Lycus thrust northwest of Olympus Mons, the Northern and Southern Tharsis graben zone, the Claritas fault, and the Solis-Lunae fold and thrust belt (Yin, 2012b). The southern Thaumasia Highlands show evidence of shortening within a crater (fig. 7). Other surficial linear features along the perimeter of the Tharsis Rise are likely strike slip faults with displacement (Andrews-Hanna, *et al.*, 2008). One of the strike slip faults on Labitas Fosse on the northwest side of the

Tharsis Rise shows a large amount of displacement (fig. 8). Faulting has also been identified through the deformation of craters within the southern area of the rise (Allemand, *et al.*, 2006) (Petrowsky, *et al.*, 2009). All of these faults show classic features that accompany large-scale plate boundaries such as displacement, mountain ranges, depressions, and age differences in lithology of the Martian surface (fig. 2).

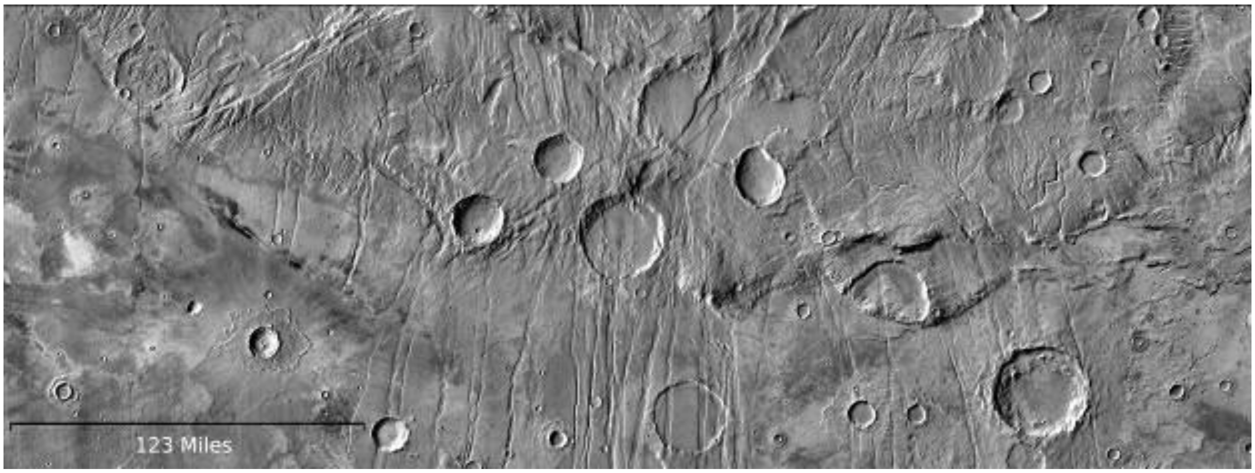

Figure 7. Thaumasia Highlands with distorted and shortened craters. The crater on the right side of the east-west ridge is shortened and slightly shifted. There are also north-south grabens cross-cutting many of the craters that result in the craters being pulled on in two directions. Themis Day IR 100m Global Mosaic V11.5 (J-Mars). Located at 280.649E, 27.912

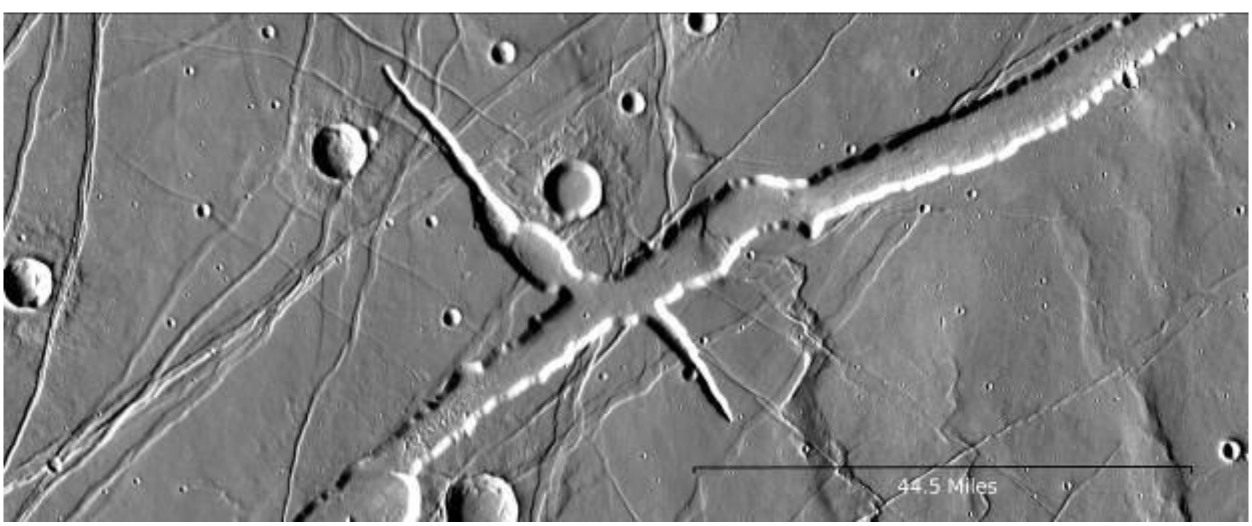

Figure 8. Displacement on the Labitas Fosse. Themis Day IR 100m Global Mosaic V11.5 (J-Mars). Located at 280.649E, 27.912

Wrinkle Ridges

Wrinkle ridges are macro scale deformation in the surface rock over large thrust faults (fig. 9), often due to fault bend folding (Plescia and Golombek, 1986). These linear features are prevalent in the Solis-Lunae fold and thrust belt and near the Thaumasia thrust. Stratigraphic relationships indicate these ridges were formed during Noacian through the early Amazonian with the bulk of their creation in the Hesperian (Andrews-Hanna, *et al.*, 2008). It is unclear if these faults are a result of fault bend folds or fault propagation folding due to the different characteristics seen with this style of faulting. Due to their 50-meter spacing, the orientations of their dips, and the amount of shortening, these faults likely extend to the bottom of the lithosphere (Golombek, 1990). Similar large scale-faulting is seen in the areas of Tempe Terra, Lunae Planum, Sinai Planum, Solis Planum, and Thaumasia Planum and is aligned perpendicular to the main body of the Tharsis rise.

Figure 9. Wrinkle ridge faulting near the Thaumasia thrust. HiRISE Image ESP_024453_1570_Red (J-Mars). Located at 280.31E -22.63

Volcanic Activity

It is unknown whether volcanic activity on Mars is a geologically active process. The past, general consensus of the volcanoes on the Tharsis Rise is that they are extinct. With new ability to analyze surface features with improved technology allows a reevaluation of this hypothesis. By using High Resolution Stereo Camera imagery along the calderas and flanking rift zones of the Tharsis Rise and Elysium Rise volcanoes, it is possible to get an accurate age dating using crater counting. The very basic premise of crater age dating states that more craters found in an area equates to greater age. There is evidence that flows on Olympus Mons and Hecates Tholus spanned 80% of the geological history of Mars, dating Olympus Mons and the creation of the Tharsis Rise to possibly early Nochian Era (Neukum, *et al.*, 2004). The five calderas that cap Olympus Mons have been dated from 100-200 Ma, happening in short succession of each other with lava flows that cascaded over the Olympus Mons scarp dating from 2.4-115 Ma (Neukum, *et al.*, 2004). This suggests that it is a possibility that Olympus Mons could have episodic activity in the future.

Age Dating

Geological maps of Mars have been made based off of rock feature types and crater count age dating (NASA). The use of this map in this study was beneficial in that tectonic relationships could be interpreted from the locations of various lithologies (fig. 10).

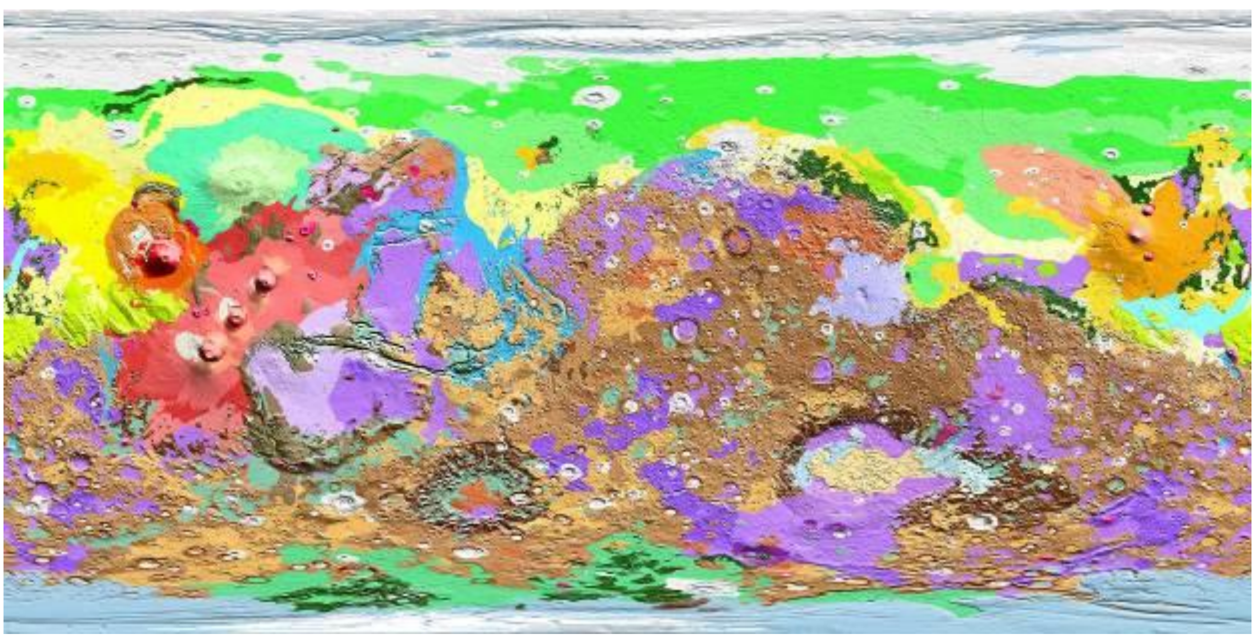

Figure 10. Geological Map of Mars (NASA).

METHODS AND RESULTS

The Tharsis Rise, including Valles Marineris, was mapped using Esri ArcMap10.2 and analyzed using traditional observations similar to field geology. Plate margins were evaluated using lineations, feature displacement, dramatic topographic differences, crater deformation, different rock units by age, and general surface topography comparisons. By using satellite imagery such as HiRISE, THEMIS, Mars Orbiter Laser Altimeter (MOLA), as well as interactive programs such as Google Mars, and J-Mars, five categories of plate margins were created within the Tharsis Rise region (table 1).

Table 1. Type of plate margins and their characteristics

Type of Plate Margin	Characteristics
Divergent	Linear features including volcanoes with regional spreading indicators such as flank fissures and parasitic calderas all aligned in the same trending direction. The age of the rock units are the same on either side of the divergent boundary.
Obduction	There are sharp changes in elevation with a non-linear boundary between the two areas. Changes in surface topography are present from relatively rough to smooth surfaces. Conjugate joints are present near the boundary. There is a change in age of the rock units.
Oblique Obduction	Sharp changes of elevation are present with a linear boundary. There is a difference in the age of the rock unit on either side. Conjugate jointing is present.
Strike Slip with visible displacement	Long lineations with displaced features on either side of the boundary. Sharp elevation changes within the lineation itself.
Strike Slip without visible displacement	Long lineations without visible displacement on the surface. Sharp elevation changes within the lineation itself.

ArcMap was used to inspect the surface for sharp lineations and known features described earlier. Conjugate joints were mapped that were visible at a 1:1,000,000 scale. These were then grouped into specific areas using natural spacing where conjugate joints were not present (fig. 11). Within these areas, rose diagrams of structural indicators such as conjugate joints, wrinkle ridges, escape structures, and grabens were constructed in ArcMap using topology and a multiple ring buffer to evaluate directions of maximum horizontal compression (fig. 12). These analyses allowed an interpretation of plate margins and their kinematic motions, yielding a broad picture of plate tectonics on the Tharsis Rise (fig. 13). Five distinct areas with unique kinematic motions and closed plate margins were identified (table 1).

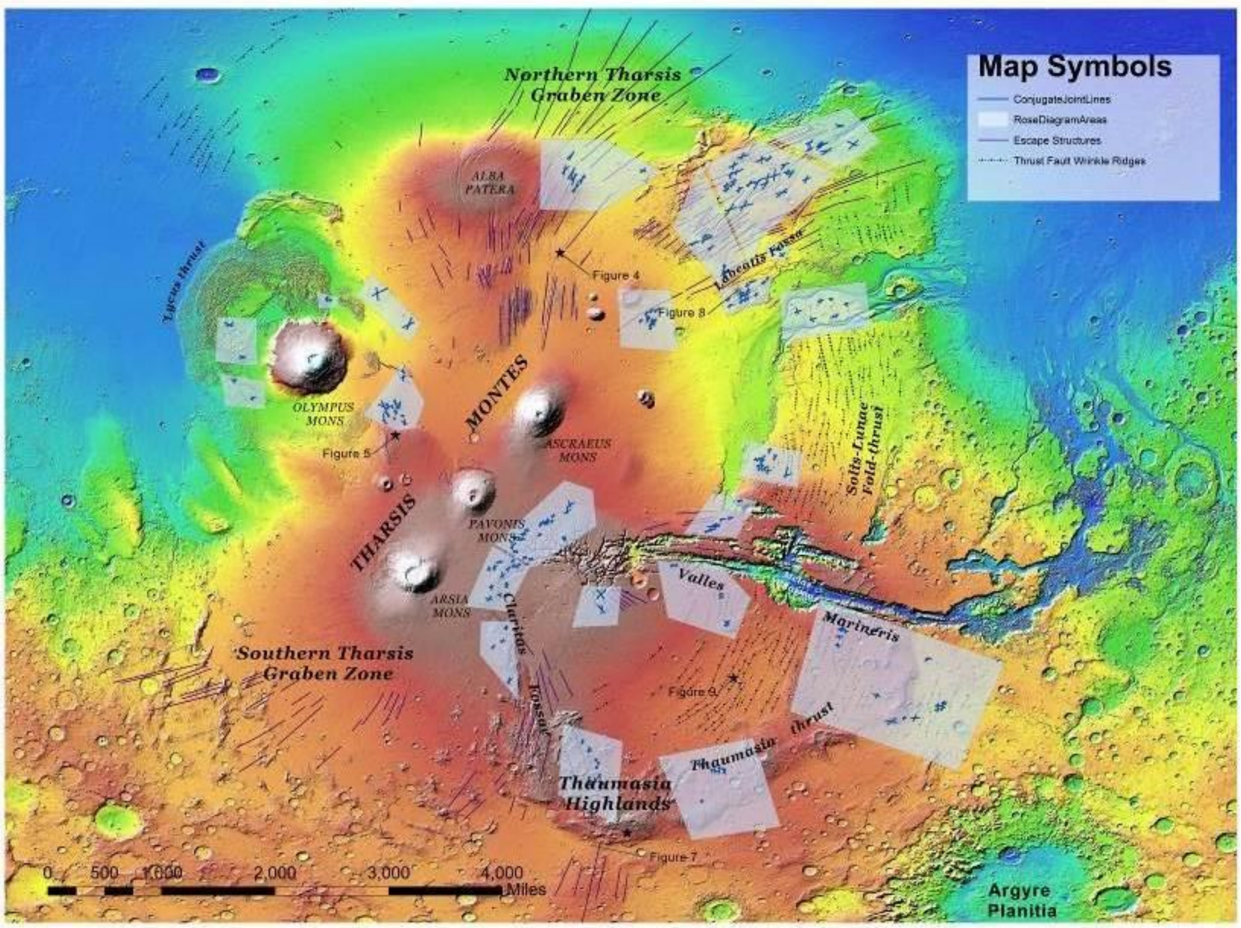

Figure 11. Mapped conjugate joints and rose diagram areas on the Tharsis rise. Background imagery from NASA.

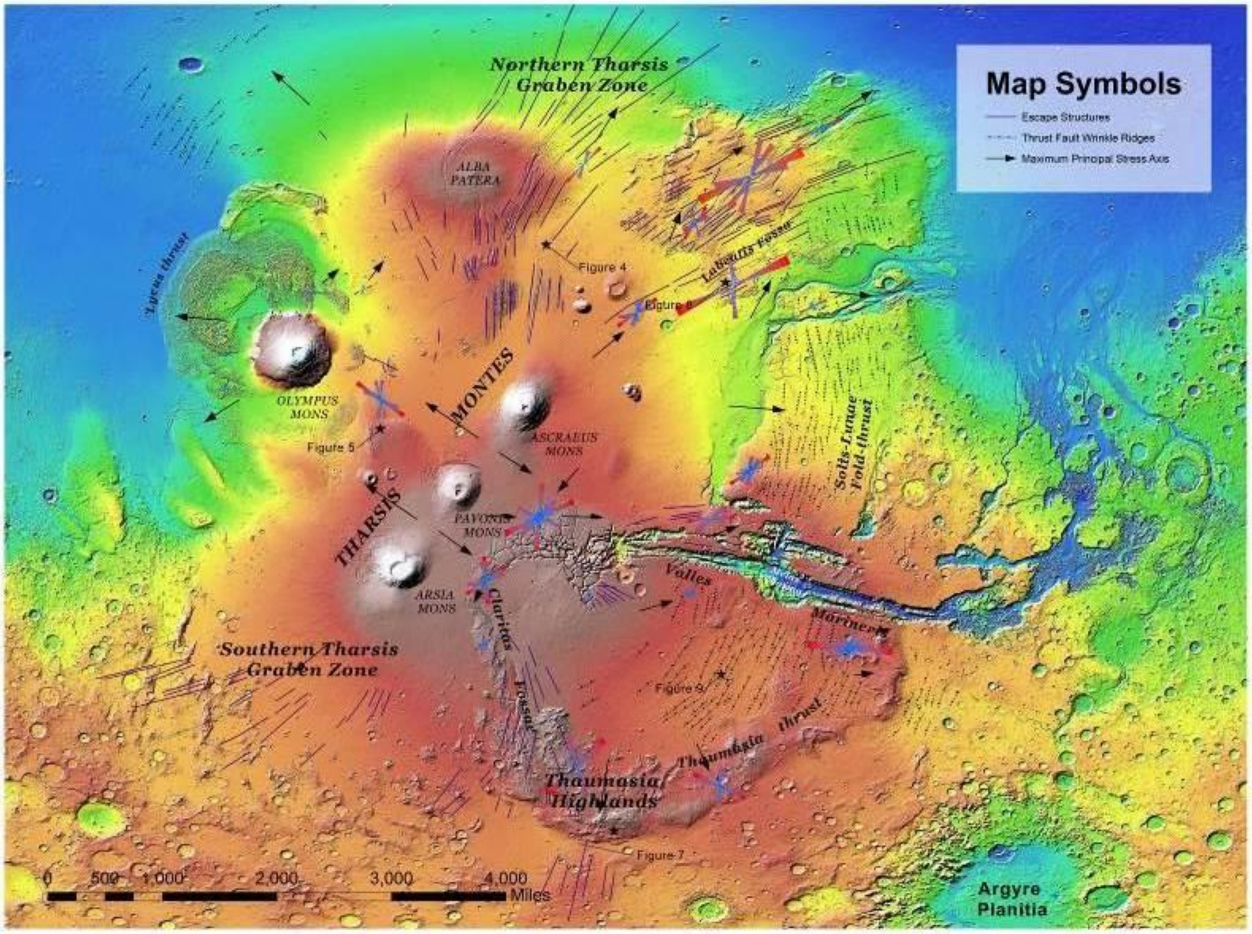

Figure 12. Rose Diagrams with maximum principal stress axes. Background imagery from NASA.

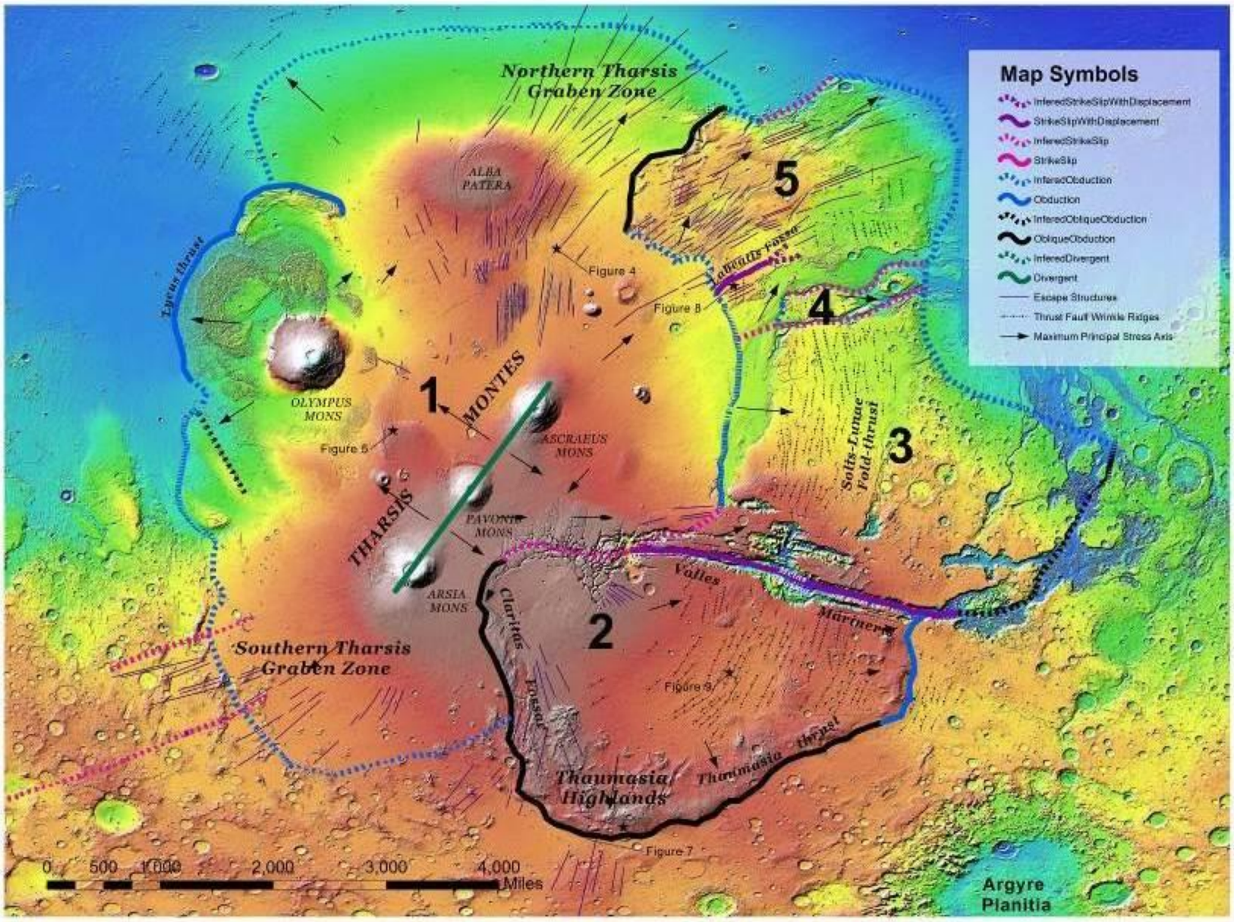

Figure 13. Tharsis Rise with plate margins and maximum principal stress axes. There are five distinctive areas on the rise that show unique kinematic movement (areas labeled 1-5). Background Imagery from NASA.

DISCUSSION

Martian tectonics surrounding the Tharsis Rise contains classic geological features similar to those seen on Earth that display a vast history of geological change. Many of the areas across the Tharsis Rise show visible displacement along tectonic features. Below is a logical summary of the region's tectonic history, including the delineation of individual plates and their current kinematic moments.

During the early Nochian, which spans the Hadean and the Archean eon on Earth, Mars was developing in a similar fashion as Earth. Slab rollback initiated by the Argyer impactor would have started early tectonics on Mars as it could have on early Earth. During this bombardment period, early in Mars' developmental history, it was struck by a large impactor that destroyed its current planetary magnetic field. With the destruction of the Martian dynamo the planet lost much of its atmosphere and protection against the solar wind. Although there is not presently a core-driven magnetic field, there is enough evidence in the crustal magnetic field that Mars did at one point have a working dynamo at its core. After this dynamo failed, hotspots of large magnitude began to rise on the surface of Mars, possibly triggered by the impactor that created Hellas Planitia, antipodal to the Tharsis Rise. Hotspot volcanism and its associated tectonic forces could have created and driven the Tharsis Rise over billions of years. These two processes could easily set the stage for widespread faulting that created planes of weakness along which movement could continue today.

Slab rollback helps to explain the creation of Valles Marineris. Part of a 1000-kilometer-scale left lateral transtentional conjugate strike slip system, Valles Marineris shows evidence of modern kinematics through displacement of young talus slopes (Yin, 2012a). As the Tharsis Rise was created, back arc basins and crustal hot spot thickening could have enabled the build-up of the rise. Currently the highest point of the rise measured by the Mars Orbital Laser Altimeter (MOLA) is at Olympus Mons averaging at 22 kilometers above Martian sea level. This rise has created a large amount of loading on the rocks on and around the rise. Using Mount Etna as a terrestrial analog, Tharsis rise would be able to activate preexisting faulting to break into plate-sized blocks that are pushed outward due to gravitational spreading and expansion due to thermal plumes. Based on these interpretations and age dating of previous flows, Olympus Mons could erupt again in the future.

CONCLUSION

Although Mars' geological past has not been directly seen, it is possible to apply many geological principals to explain its surficial features. Many scientists have put great effort into deciphering the Tharsis rise. Using the research of others, as well as using remote sensing to gather evidence of classic geological landforms, we conclude there are modern processes at work on the rise. We identified surface features that are closely correlated with plate boundaries on Earth such as strike-slip systems, mountain ranges, abrupt contacts of differing rock ages, and distinct topographic features. Geological structures in the form of conjugate jointing, escape structures, wrinkle ridge faulting, and strike-slip faulting yielded interpretations of plate motions. During this study, five distinct areas on the Tharsis Rise show evidence of movement in a unique direction and have features we interpret as plate boundaries. Further questions for study include continued recognition and analysis of conjugate joint systems in and around the rise and continued age dating of these conjugate joint systems, which will yield a more accurate picture of kinematic processes over geological time.

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